EARTHQUAKES

# Tsunamigenic Middle Earth

Violent uplift of western Crete in AD 365 generated a Mediterranean-wide tsunami that tossed boats onto house-tops in Alexandria, Egypt. Although a similar earthquake may not recur for 5,000 years, contiguous fault segments could rupture sooner.

Roger Bilham
**is at the University of Colorado, Boulder, Colorado 80309-0399, USA.**
**e-mail: bilham@colorado.edu**

Two decades after the destruction of Alexandria by a tsunami in AD 365, Ammianus Marcellinus wrote “the great mass of waters returning when it was least expected, killed many thousands of men by drowning; and by the swift recoil of the eddying tides a number of the shipwrecked persons lay floating on their backs or on their faces” (cited by ref.1). His words conjure graphic images of Aceh, or Sri Lanka in the aftermath of the 2004 Sumatra/Andaman earthquake. That the Mediterranean region with its growing coastal population in excess of 130 million, and twice as many annual tourists[2,3], could host a large tsunami at any moment, is cause for considerable unease among a dozen European, Middle Eastern and African nations. Calculations by Shaw *et al.* on page 268 of this issue[1] are the most recent to quantify the path of the AD 365 tsunami from tectonic origin to coastal targets, and the first to speculate on the recurrence interval of such a disaster.

For at least 200 years the “day of horror” in Egypt was commemorated annually by survivors and their descendants (Sozomenus, cited by ref. 4). As in Sri Lanka, the tsunami had come out of the blue, and until recently the epicentre of the seismic shaking causal to the Alexandria tsunami was not at all clear. Later historians had muddled the tsunami with several other disastrous earthquakes that occurred during the collapse of the Roman Empire following the death of Julian in AD 363[4–8]. For some historians, it was sufficient to note that the fall of Rome was accompanied by an earthquake that engulfed the entire world — “*terraemotu per totum orbem facto*” (Migne, cited by ref. 14).

However, for more than 150 years it has been known that something very unusual occurred in western Crete. Captain Thomas Spratt, while mapping the Aegean Sea for the British Admiralty in 1851, was forced to conclude that abandoned Roman and Greek ports now high and dry owed their plight to a recent upheaval of the land[9]. His explanation required no earthquake but there is abundant evidence recorded for violent shaking of the island shortly after AD 360 amid the ruins of abandoned cities, where skeletons have been found crushed beneath fallen masonry with dated coins on their persons[10]. The link between this destructive shaking and the uplift of the western end of Crete tightened in the 1980s when shells of marine molluscs killed in their growth positions were subjected to radiocarbon dating[7]. Upheaval apparently occurred within 200 years of the tsunami, a date that Shaw *et al.* have now narrowed to within a few decades using refined radiometric dating methods.

The northeasterly slope to the raised shorelines in western Crete is suggestive of slip on a subsurface thrust fault heaving the island up to the southwest. Several previous investigators have recognized the most likely causal culprit as the Hellenic subduction zone, which marks the descent of the African plate beneath the Aegean plate at ≈35 mm yr$^{-1}$ (refs 11–16). A difficulty with this obvious attribution is that geodetic studies reveal the interface to be sliding aseismically at present, unable to accumulate the elastic energy needed to drive a great earthquake. Although all elastic models agree that the most likely rupture plane strikes parallel to the trench, and that the causal earthquake must have had a whopping magnitude (Mw) of 8.5, differences remain as to the most likely dimensions of the rupture and the amount of slip (Table 1). Some of these extreme solutions are physically implausible, especially those that require brittle failure far below 40 km depths where plastic rheologies are thought to prevail.

The model used by Shaw *et al.* is novel in that it invokes substantial (20 ± 5 m) slip on a 100 × 90 km$^2$ fault that is distinct, and set back from, the Hellenic subduction zone, dipping beneath Crete at an angle of 30°. This overcomes problems with deep rupture, but introduces new interesting problems — if the fault that slipped is not on the plate interface, how is it driven and how frequently does it slip? The good news offered by these authors is that African collision may take five millenia to regenerate the stress that drove the AD 365 event. The bad news is that a handful of contiguous fault patches with similar geometries, and under similar stress, could slip and cause megaquakes at any time.

By imposing the surface deformation expected from this and other similar ruptures as instantaneous perturbations to the sea surface, it is relatively straightforward to calculate the propagation paths and amplitudes

**Table 1** **Rupture parameters estimated for the AD 365 western Crete earthquake.**

| Strike (degrees) | Dip (degrees) | Depth (km) | Length (km) | Width (km) | Mean slip (m) | Mw magnitude | Reference |
|---|---|---|---|---|---|---|---|
| 315 | 30±5 | 0–45 | 100 | 90±15 | 20±5 | 8.4±0.1 | 1* (Shaw *et al.*) |
| 312 | 20 | – | 233 | 38 | 10 | 8.3 | 11[†] |
| 292.5 | 40 | 0–70 | 105 | 100 | 16 | 8.5 | 14* |
| 315 | 35 | 5–50 | 160 | 80 | 8.9[‡] | 8.5 | 15* |
| 297 | 13 | – | 145 | 130 | 12[§] | 8.5 | 16* |
| 314 | 35 | 5–54 | 130 | 86 | 17.5 | 8.4 | 17[†] |

*Calculated from uplift of marine terraces [†]Adopted values [‡]Variable spatial slip [§]Inferred from stated Mw and geometry

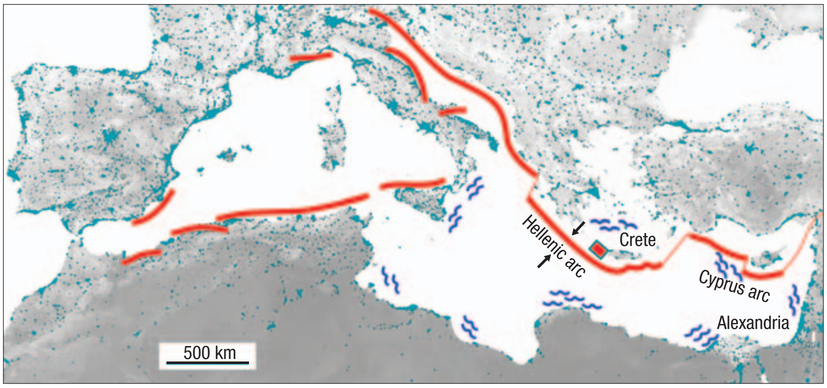

**Figure 1** Tsunami sources and Mediterranean population targets. Simplified potential tsunami source regions (red lines)[11,12,17] and the modest inferred source region for the magnitude 8.5 earthquake in western Crete (rectangle) whose tsunami destroyed coastal communities in AD 365. Arrows indicate Africa/Aegean convergence. The blue wavy lines symbolize coastal tsunami arrivals. Turquoise spots on the map correspond to village and city lights that are here used as a proxy for population density (night luminosity imagery from http://visibleearth.nasa.gov/view_detail.php?id=1438). Huge populations are preferentially concentrated along the coast and are expected to grow rapidly in the next few decades[3].

of tsunami as they ripple around the Mediterranean Sea. Alarmingly, many transit times of tsunami to close-by coastal populations are unforgivingly short — some less than 15 minutes[11,12,17]. Within 30 minutes of the AD 365 earthquake, the coast of North Africa had received a broadside volley of damaging waves. Simultaneously a northward-travelling wave had swamped the southern coasts of a dozen Aegean islands and Greece. Thirty minutes later, waves with amplitudes of up to 5 m had reached Italy, Sicily and southeast Turkey. And an hour later, the coasts of the Nile delta, the Levant and Cyprus had all been overwhelmed. Calculations of run-up of the AD 365 tsunami require detailed coastal slope data that have yet to be incorporated[12], but it is likely that the wave surged onshore with maximum depths of ~5 m in many locations[17].

With tectonic sources and target populations facing each other throughout the Mediterranean region (Fig. 1), the first warning for many coastal citizens of Middle Earth following a future megaquake may well be seismic waves, rather than the wail of sirens. However, for the largest tsunami, with distant reach and damaging amplitude, more than an hour of warning may be available. Either way, nobody doubts that tsunami will recur.

### References

1. Shaw *et al. Nature Geosci.* **1,** 268–276 (2008).
2. Hinrichsen, D. *Coastal Waters of the World* (Island Press, 1998).
3. Cori, B. *J. Coastal Conservation* **5,** 105–1127 (1999).
4. Stiros, S. C. *J. Struct. Geol.* **23,** 545–562 (2001).
5. Ambraseys, N. N., Melville, C. P. & Adams, R. D. *The Seismicity of Egypt, Arabia and the Red Sea* (Cambridge Univ. Press., Cambridge, UK, 1994).
6. Guidoboni, E., Comastri A. & Triana G. *Catalogue of Ancient Earthquakes in the Mediterranean up to the Tenth Century* (Instuto Nationale di Geofisica, Roma, 1994).
7. Pirazolli, P.A., Laborel, J. & Stiros, S. C. *J. Geophys. Res.* **101,** 6083–7097 (1996).
8. Van Nuffelen, P. *Classical Quart.* **56,** 657–661 (2006).
9. Spratt, T. A. B. *Travels and Researches in Crete* Vol. 2 (John Van Voorst, London, 1865).
10. Stiros, S. C. & Papageorgiou, S. *J. Seismol,* **5,** 381–397 (2001).
11. Tinti, S., Armigliato, A., Pagnoni, G. & F. Zaniboni *ISET J. Earthquake Technol.* **42,** 171–188 (2005).
12. Yolsal, S., Taymaz, T. & Yalçiner, A. C. *Geol Soc. Lond. Spec. Publ.* **291,** 201–230 (2007).
13. Taymaz, T., Yilmaz, Y. & Dilek, Y. *Geol. Soc. Lond. Spec. Publ.* **291,** 1–16 (2007).
14. Stiros, S. C. & Drakos, A. A. *Z. Geomorphol.* **146** (suppl), 123–137 (2006).
15. Papadimitriou, E. E. & Krakostas V. G. *Acta Geophysica* doi: 10.2478/s11600-008-0001-6 (2008).
16. Fischer, K. D. & Babeyko, A. *Geophys. Res. Abstr.* **9,** 09458 (2007).
17. Lorito, S, Tiberti, M. M. Basili, R. Pitanesi & Valensise, G. *J. Geophys. Res.* **113,** doi: 10.1029/2007JB004943 (2007).

## GEOMORPHOLOGY

# Muddying the waters

ISTOCKPHOTO.COM/ DON MACE

The annual migration of salmon upstream is a spectacular sight to tourists and hungry bears alike (see image). Their arduous swim is largely seen as the response to an internal drive to reproduce, but the effects of the journey go beyond the procreation of this predatory fish.

Once the salmon have arrived at their upstream spawning areas, hard-working female fish use their fins and bodies to mobilize sediments lining the streambed, digging small holes, or redds, of up to 50 cm deep in which they lay their eggs. In particularly popular mating areas, the redds can disturb the entire channel bed.

Although the hummocky surface of the nests is readily visible from August to May, the impact of the redds on overall sediment transport within salmon-filled streams has been unclear. Marwan Hassan at the University of British Columbia, Canada, and colleagues therefore used bed-load traps and magnetically tagged particles to analyse the effects of salmon activity in the Fraser River basin, Canada (*Geophys. Res. Lett.* **35,** L04405; 2008).

In individual watersheds, salmon were responsible for up to 60% of sediments mobilized each year, mainly in the form of clays, silts and sands, which are easily resuspended by the digging fish. On average, salmon moved over half as much of these sediments as flood events did during the five years of the study. In years with minimal flooding, salmon were actually the primary drivers of sediment movement.

In their quest to dig a home for their offspring, salmon become a first-order control on sediment transport in their home streams. The relationship between habitat and biology is clearly not a one-way street.

**Alicia Newton**